U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-278 997

The Ozone Problem in the Norfolk, Virginia Area

Environmental Sciences Research Lab, Research Triangle Park, N C

Jan 78

PB 278 997

EPA-600/4-78-006
January 1978

Environmental Monitoring Series

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Development, U.S. Environmental Protection Agency, have been grouped into nine series. These nine broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The nine series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies
6. Scientific and Technical Assessment Reports (STAR)
7. Interagency Energy-Environment Research and Development
8. "Special" Reports
9. Miscellaneous Reports

This report has been assigned to the ENVIRONMENTAL MONITORING series. This series describes research conducted to develop new or improved methods and instrumentation for the identification and quantification of environmental pollutants at the lowest conceivably significant concentrations. It also includes studies to determine the ambient concentrations of pollutants in the environment and/or the variance of pollutants as a function of time or meteorological factors.

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

TECHNICAL REPORT DATA (Please read Instructions on the reverse before completing)		
1. REPORT NO. EPA-600/4-78-006	2.	3. RECIPIENT'S ACCESSION NO. PB278997
4. TITLE AND SUBTITLE THE OZONE PROBLEM IN THE NORFOLK, VIRGINIA AREA		5. REPORT DATE January 1978 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Gerard A. DeMarrais*		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Environmental Sciences Research Laboratory Office of Research and Development U.S. Environmental Protection Agency Research Triangle Park, NC 27711		10. PROGRAM ELEMENT NO. 1AA603 AD-07 (FY-77) 11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS Environmental Sciences Research Laboratory - RTP, NC Office of Research and Development U.S. Environmental Protection Agency Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Inhouse 3/76-8/77 14. SPONSORING AGENCY CODE EPA/600/09
15. SUPPLEMENTARY NOTES *On assignment from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce.		

16. ABSTRACT

The area of Norfolk, Virginia, being well displaced from large urban centers and having the Atlantic Ocean at its eastern border, appears to be sheltered from air pollution originating in other urban sources. The area frequently, however, records high concentrations of ozone. Maximum hourly concentrations exceeded 80 parts per billion in the Hampton Roads area during 40 percent of the days in July and August 1974. The ozone data for that period are analyzed in this report. Emphasis is given to the potential for the high concentrations to have been transported in from distant upwind urban areas. Other meteorological phenomena associated with the high concentrations of ozone are also discussed.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
*Air pollution *Ozone *Meteorological data Evaluation	Norfolk, VA	13B 07B 04B

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (This Report)	21. NO. OF PAGES
RELEASE TO PUBLIC	UNCLASSIFIED	31
	20. SECURITY CLASS (This page) UNCLASSIFIED	22. PRICE PCA03 PFA01

EPA Form 2220-1 (9-73)

EPA-600/4-78-006
January 1978

THE OZONE PROBLEM IN THE NORFOLK, VIRGINIA AREA

by

Gerard A. DeMarrais
Meteorology and Assessment Division
Environmental Sciences Research Laboratory
Research Triangle Park, N.C. 27711

ENVIRONMENTAL SCIENCES RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, N.C. 22711

DISCLAIMER

This report has been reviewed by the Office of Research and Development, U.S. Environmental Protection Agency, and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

Mr. DeMarrais is a meteorologist in the Meteorology and Assessment Division, Environmental Sciences Research Laboratory, Environmental Research Center, Research Triangle Park, N.C. 27711. He is on assignment from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

ABSTRACT

The area of Norfolk, Virginia, being well displaced from large urban centers and having the Atlantic Ocean at its eastern border, appears to be sheltered from air pollution originating in other urban sources. The area frequently, however, records high concentrations of ozone. Maximum hourly concentrations exceeded 80 parts per billion in the Norfolk area during 40 percent of the days in July and August 1974. The ozone data for that period are analyzed in this report. Emphasis is given to the potential for the high concentrations to have been transported in from distant upwind urban areas. Other meteorological phenomena associated with the high concentrations of ozone are also discussed.

CONTENTS

Abstract iii

Figures vi

Tables vi

1. Introduction 1

2. Conclusions 2

3. Background and Methods 4

Urban complex 4

Data collection stations 4

The meteorology associated with ozone problems in other areas 4

The diurnal variation of ozone concentration and the associated meteorology 5

Basic data and input considerations 6

4. Results 9

Ozone concentrations and the prior 24-hour air movement . . 9

High ozone concentrations and the associated meteorology . . 9

Analyses of episode data 10

July 13-16, 1974 11

August 18-21, 1974 12

References 14
15

Preceding page blank

FIGURES

Number		Page
1	Ozone sampling stations, Norfolk area.	16
2	48-hour backward trajectories, surface to 700 meter layer, 13-16 July, 1974. 12-hour intervals	17
3	48-hour backward trajectories, surface to 700 meter layer, 18-21 August, 1974. 12-hour intervals	18

TABLES

1	Maximum Afternoon Ozone Concentration and Past 24-Hour Air Movement	19-20
2	Meteorology on Days When the Ozone Standard Was Violated	21-22

SECTION 1

INTRODUCTION

High ozone concentrations in the area of Norfolk, Virginia, were reported several years ago and it was suggested that this ozone problem was not associated with the local automotive traffic[1]. Since that time, the Virginia pollution control agency has reported that the violations of the National Ambient Air Quality Standard (NAAQS) of 160 micrograms per cubic meter or 80 parts per billion (ppb) were numerous and were increasing[2]. Since a better understanding of the meteorology associated with the high concentrations, particularly long range transport, could aid in the formulation of a practical abatement strategy, this investigation was undertaken.

The Norfolk area appears to be favorably located with regard to minimizing anthropogenic air pollution problems associated with transport from distant population centers. The Atlantic Ocean is to the NE (standard directional abbreviations are used) through SE of the area; only widely scattered, relatively small cities are to the S through W; and urban complexes are to the NW through N. Richmond, 135 kilometers (km) to the NW is the closest large city. As to other cities to the NW and N, their metropolitan areas are extensive, but their distances from Norfolk are large. Washington is 300 km, Baltimore 325 km, Philadelphia 375 km, New York 550 km, and Pittsburgh 650 km from the Norfolk area.

In order to show the probable contribution of these distant upwind urban source areas, trajectory analyses[3] of layers of air between the surface and 700 meters (m) above the surface are employed. Other meteorological phenomena are discussed when it is apparent that they contributed to the high concentrations. The ozone data for July and August 1974 are analyzed.

SECTION 2

CONCLUSIONS

On the basis of the analyses of the July-August 1974 Norfolk area data, the following conclusions are drawn:

1. Twenty-four hour trajectories indicate that high ozone concentrations (>80 ppb) are more likely to occur when the prior flow is from over large urban source areas than when the flow is from over areas without such source areas.

2. High concentrations of ozone occured in conjunction with a wide range of meteorological conditions: temperatures were just as often below as above normal; average daily daytime (7 a.m. to 5 p.m.) wind speeds ranged from 2.5 mps (light) to 6.8 mps (strong) and directions varied over a wide range; solar radiation, based on sunshine records, ranged from 3 to 100 percent; rainfall occurred many times, but more often there was no rain; and high concentrations occurred on days with frontal activity, but more often on days without fronts. High concentrations of ozone in the Norfolk area were not associated with any one set of meteorological conditions such as clear skies, low wind speeds and relatively high temperatures.

3. Analyses of data during an episode when high concentrations were associated with obvious transport from distant urban complexes to the N and NW of Norfolk, showed the concentrations were high when the air came from the potential source areas, decreased when the flow came from another direction and then increased when the air again came from the source areas.

4. Analyses of data during an episode when high concentrations were associated with a flow from over the Ocean showed that the air was coming by a circuitous route from over urban source complexes to the N and NW. In spite of a 36-hour transit over the Ocean (no contact with a potential source) the air which had been over the urban complexes arrived in the

Norfolk area with high concentrations of ozone. During one day of this episode the winds were strong enough (about 7 mps) to minimize any significant local contribution to high ozone concentrations; long range transport from urban complexes to the N and NW was a major factor in the observed high concentrations of ozone.

SECTION 3

BACKGROUND AND METHODS

URBAN COMPLEX

The Norfolk area as shown in Figure 1, includes the cities of Hampton, Newport News, Norfolk, and Portsmouth. The area is almost surrounded by water and is traversed by numerous rivers and waterways. Its average elevation above mean sea level is about 5 meters. The land is level. A square of about 30 km on a side includes the 4 major cities in the Norfolk area. The area has many heavily traveled roads and numerous military bases. It handles a large amount of shipping along its extensive coastline. There are numerous hydrocarbon storage sites. The Great Dismal Swamp, which covers most of an 80- by 80-km square area along the coasts of Virginia and North Carolina, is just south of Norfolk.

DATA COLLECTION STATIONS

In the Norfolk area the state of Virginia collects hourly ozone data at 3 stations, which are shown in Figure 1. Station 179 is located at the Virginia School for the Deaf and Blind in Hampton. The site is about 1 km from the shoreline of Hampton Roads, and heavy traffic passes within a few blocks of the site. Station 181 is at the Norfolk Regional Airport, about 3 km from the shoreline of Chesapeake Bay and less than 2 km from the heavily travelled Interstate 64. Station 183, Nansemond, is on the campus of Tidewater College, about 0.3 km from the shore of Hampton Roads and 5 km north of U.S. 17. The Hampton and Norfolk stations have chemiluminescense instruments, and the Nansemond station uses an ultraviolet Dasibi instrument.

THE METEOROLOGY ASSOCIATED WITH OZONE PROBLEMS IN OTHER AREAS

High ozone concentrations have been investigated for 30 years[4] and have been found to occur with certain meteorological conditions[4-9]. Chock

et al.[5] reported that solar radiation intensity and temperature are directly related while wind speeds, because of their diluting effects, are inversely related to the ozone problem in Los Angeles. Ozone buildup was generally noted about 2 hours after initial radiation[6] of ozone precursors, so wind speed is important in moving precursors and ozone from local to downwind areas. Anlauf et al.[7], studying high concentrations over Lake Ontario near Toronto, found that the concentrations correlated very well with temperature and local wind direction and only partially with global radiation. Tiao et al.[8] developed an empirical model for the Los Angeles photochemical oxidant (mostly ozone) problem and they found that intense solar radiation, high temperatures and low wind speeds were associated with the worst episodes. Lyons and Cole[9] suggested that long range ($\geq$ 200 km) transport of oxidant pollutants on the western side of anticyclones caused high concentrations to be displaced many km from the sources of ozone precursors. Lea[10] reported that high surface concentrations could be associated with transport by the winds aloft.

THE DIURNAL VARIATION OF OZONE CONCENTRATION AND THE ASSOCIATED METEOROLOGY

The typical diurnal variation of surface ozone concentrations is as follows[6,7,8]: low at night and in the early morning hours; increasing rapidly starting 7 to 9 a.m. and peaking around 2 to 3 p.m.; and then declining through the remainder of the afternoon until the low nighttime values are first observed around 8 to 10 p.m.

Early investigators[4] described the high ozone concentrations as a local photochemical phenomenon. Solar radiation reacting with the precursors of ozone emitted by automobiles and industry brought about the high concentrations. In 1961[6] it was reported that the photochemical production of ozone in air with precursors exceeded ozone destruction (for example, by NO scavenging and surface uptake) at the surface from 2 to 7 hours after the photochemical reactions were initiated by irradiation. This timing readily accounted for the increases in concentrations starting in the morning, the peaking in the early afternoon and then the declining. After several hours of destruction exceeding production the low nighttime concentrations are observed. The relatively high concentrations of the daytime generally extended from a few km downwind from the sources to as many km as the surface winds advected the polluted layers in the daytime period. The relatively high daytime contributions are attributed to local

problems dependent on nearby emissions and surface advection on the day of the occurrence of the high concentration.

Lea[10] first reported that there could be a contribution from aloft to high concentrations of ozone at the surface and that this contribution could be associated with long-range transport. During the daytime, the upward currents of vertical mixing carry ozone and ozone precursors aloft. At night, when the vertical mixing is generally suppressed and restricted to a shallow layer near the surface, the ozone aloft remains intact while that at the surface is destroyed by reaction with fresh NO_x emissions and surface deposition. This diurnal variation in vertical mixing coupled with ozone aloft produces, at the surface, a variation in ozone concentration similar to that produced by photochemical reactions in the layers of air advected at the surface; at night and during the early morning hours no ozone is brought to the surface; as vertical mixing increases soon after sunrise there is a marked increase in the ozone brought to the surface; when vertical mixing reaches a maximum early in the afternoon ozone contained in the whole mixing layer is subject to downward vertical mixing and concentrations at the surface are relatively high; after the maximum vertical mixing occurs the concentrations at the surface decrease as there is no fresh ozone from aloft being brought into the mixing layer. Thus, it is very difficult to separate the ozone concentrations associated with nearby (local) upwind emissions and those associated with long-range transport coupled with vertical mixing because each produces a similar pattern.

BASIC DATA AND INPUT CONSIDERATIONS

The hourly data for the three ozone monitoring stations for July and August 1974, available from the National Aerometric Data Bank of the U.S. Environmental Protection Agency, are used in most of the analyses. The initial analyses compare the daily, maximum, hourly concentrations with trajectories for the prior 24 hours. The second comparison is of days having an ozone standard violation ($\geq$80 ppb) with the occurrence of specific meteorological conditions. In the final evaluation, periods of several consecutive days (episodes) with ozone standard violations are compared to 48-hour trajectories. In this report, when the NAAQS is violated, a concentration is called high.

The size of the Norfolk heavily built-up and industrialized area and the

locations of the monitoring instruments are important in regard to the potential for the local area to be the cause of the high ozone concentrations. The locally generated precursors originate for the most part in the 30-km by 30-km area and the locations of the monitors are such that they are seldom more than 15 km from the local sources. With the man-made precursors requiring 2 hours or more after emission to be converted to ozone[6], a wind of 2 mps in the same direction for 2 hours would move the local precursors beyond the monitors before the ozone formed. Thus high ozone concentrations due to local emissions would generally be associated with weak winds (< 2 mps) or those that allow for little displacement.

The trajectory analyses are based on the Heffter-Taylor model[3] and are calculated for the surface to 700-meter layer. Analyses of the diurnal variation of the August-July 1974 ozone data showed that concentrations were usually low at night, increased rather substantially 2 or 3 hours after sunrise (about 5 a.m.; all times are Eastern Standard Time), and peaked in early or mid-afternoon. In this paper the 24-hour trajectory analyses extend back from 1 p.m. (the ending time just prior to the normal occurrence of the ozone peak and the time when pollutants at distant upwind locations would be mixed to their greatest heights). A resultant wind for 24-hours from the NW, averaging only 3.5 mps, could bring in air to Norfolk from the Washington, D.C. area; 24-hour trajectories would readily indicate when the closer metropolitan areas may be contributing to the ozone concentrations in Norfolk. In the analyses of ozone episodes, 48-hour trajectories ending at 7 a.m. and 1 p.m. are used. The longer trajectories serve the purpose of showing when prolonged passages over extensive built-up areas occurred and of sometimes showing when the passage over a relatively underdeveloped area in the past 24 hours was preceded by passage over a possible source area.

The trajectory analyses[3] are calculated from the wind data from the rawinsonde observations scheduled at 7 a.m. and 7 p.m. and winds aloft observations made at 1 a.m. and 1 p.m. each day. In the basic calculation, a point along the trajectory is determined every 3 hours and data within a radius of 300 nautical miles (556 km) are evaluated. The model includes a distance weighting factor (the closest observations receive the greatest weight), an alignment weighting factor (observations upwind and downwind receive the greatest weight),

and a height weighting factor (the thicker the subpart of the layer which the wind represents, the greater the weight). Trajectory segments are usually started from a source or receptor four times daily, 1 and 7 a.m. and 1 and 7 p.m. Obviously these trajectories are approximations; they become progressively less reliable with each added segment. A point on the trajectory indicates the general area and not a specific location where the air was located at an earlier time.

The local meteorological data are recorded hourly[11] at the Norfolk Regional Airport and 3-hourly data are published[12]. The airport data utilized are: winds; temperature departures from normal; percent of possible sunshine (in place of solar radiation measurements, which are not available); occurrences of rain; and sky condition (clear, cloudy, partly cloudy). The Daily Weather Map[13] was used to determine the locations of high pressure areas (highs) and fronts. The Daily Weather Map shows two pertinent maps for each day based on 7 a.m. observations; one map is for the surface and the other for 500 millibars (about 5500 m above sea level).

SECTION 4

RESULTS

OZONE CONCENTRATIONS AND THE PRIOR 24-HOUR AIR MOVEMENT

The highest hourly afternoon concentration for each station for each day in July and August 1974 and the results of the 24-hour trajectory analyses are listed in Table 1. The trajectories were used to determine: (1) the approximate direction from which the air came during the 24 hours prior to 1 p.m. and (2) the name of any large urban source area that the air likely traversed when the flow was from the WNW through NE. The tabulation shows that trajectories from the ENE through W, from over areas without large urban source areas, occurred on 41 days and there were violations on 12 days (29 percent of the non-urban trajectories). As already noted, passage over relatively undeveloped areas during the most recent 24-hours does not preclude passage over a source area at a slightly earlier time and a possible contribution to the Norfolk ozone concentrations by long distance transport. Air movement from the WNW through NE is from over the area with urban complexes and occurred on 20 days with 13 of these days having violations (65 percent of the urban trajectories). This is an indication that part of the Norfolk area ozone problem may be partially caused by the upwind contribution of distant large urban source areas.

HIGH OZONE CONCENTRATIONS AND THE ASSOCIATED METEOROLOGY

The NAAQS was violated at one or more stations (see Table 1) on 25 days in July and August 1974. The meteorology for these days is summarized in Table 2. Low wind speeds or stagnation conditions have been associated with local ozone problems in other areas[4-6,8].

The daily average wind speeds (Table 2) for the hours of the day when the concentrations were usually elevated, 7 a.m. to 5 p.m., show that weak winds (< 2 mps) which would allow local emissions to be converted to ozone before reaching the monitors did not occur. Since Norfolk has a nocturnal

offshore flow and an onshore (sea breeze) flow in the daytime, the wind reversal which occurs early in the daytime could cause a back-and-forth motion and allow time for ozone formation of the locally emitted precursors. As shown in Table 2, these reversals occurred on 40 percent of the days (one reversal was atypical as an offshore flow replaced an onshore flow) and on half of these days the speeds averaged 4.0 mps or more; back-and-forth motion which might allow for ozone formation did not appear to be a significant factor. The temperature departures from normal show that violations occurred just as frequently with low as with high temperatures. The location of the Norfolk area in relation to the center of high pressure is different from that found elsewhere[9] in that the area was on the western side of the high on only 1 of the 25 violation-days. However, the location of Norfolk with regard to sources precludes high concentration of ozone on the western side of a high. The southeast to southwest winds on the west side of a high would bring in air from an area with no urban complexes. The indirect measure of solar radiation intensity, percent of possible sunshine, indicates that intense solar radiation, as was found to be important in other studies[4-6,8], is not a prerequisite for high concentrations in the Norfolk area; it is assumed that the wide range of percentage shows that the solar radiation varied considerably with violation days. Rain, because of washout and frontal activity (since it brings in a new air mass), are generally thought to have a cleaning effect on the air over an area. One or both of these cleansing phenomena occurred on 44 percent of the violation days (see Table 2), again indicating that high ozone concentrations occurred during a wide range of meteorological conditions.

ANALYSES OF EPISODE DATA

The 24-hour trajectory analyses indicated that high ozone concentrations were frequently associated with prior air movement over large, urban source areas. In order to better illustrate the relationship between high concentrations and long range transport, 2 episodes, or periods of several consecutive days with NAAQS violations, were selected for detailed analyses. The 7 a.m. trajectories are included in these analyses of the episodes to show the probable source of the air which arrived in the morning and could have been associated with the marked increases in ozone concentrations during the morning hours; peak concentrations generally occurred in the afternoon, but many morning

concentrations exceeded the NAAQS. The first episode demonstrates how obvious flows from large urban source areas affected the area and the second shows high concentrations were associated with circuitous long distance travel. In explaining these long distance transport phenomena the diurnal variation in concentrations of ozone and other meteorological phenomena which contributed to the high concentrations are also discussed.

JULY 13-16, 1974

The trajectory calculations for July 13 through 16 are seen in Figure 2. The surface winds (Table 2) were moderate and from over the land (from the NW) throughout the daytime period on the 13th and 14th and were stronger and from the land (more W) on the 15th. On the first 2 days the trajectories showed that the air had come from over urban complexes to the N and NW. On the third day, the 15th, the air came from the relatively clean area to the W. There were still violations on this day, but the concentrations decreased from the 14th by about 35 percent (see Table 1). The trajectories for 7 a.m. and 1 p.m. of the 16th, when considered in conjunction with the timing of the high concentrations of ozone, dramatically show the effect of source area. On the first 3 days the concentrations of ozone increased rapidly in the morning and the NAAQS was exceeded around noon to 1 p.m. The trajectory for 7 a.m. on the 16th shows the air over Norfolk came from the W and the associated concentrations remained relatively low through early afternoon. The 1 p.m. trajectory, due to the passage of a cold front, shows an air flow from over urban complexes to the N and NW and the initial violation of the NAAQS occurred about 3 hours later than it did on prior days.

During this episode the high concentrations were associated with an obvious flow from over urban complexes to the N and NW. The source-receptor relationship was obvious on the first two days. On the third day concentrations were lower as the air came from relatively source-free areas and on the fourth day it appeared there would be no violations as the air continued to flow from the W. However, with the drastic shift in trajectory, due to the passage of the cold front, the concentrations did exceed the NAAQS as air came in from the suspected source areas.

AUGUST 18-21

The first 3 days comprised the episode; data for the 4th day show the conditions that accompanied a marked decrease in concentrations. The daytime surface winds (Table 2) showed that on the 18th there was a moderate wind which shifted from offshore to onshore, a moderate onshore flow on the 19th and a strong onshore flow on the 20th. The trajectories are shown in Figure 3. On August 18th, the air came from over large cities to the NW and W as the trajectories extended almost 1000 km; the air movement was relatively rapid. The high concentrations on the 19th, according to Table 1 (24-hour trajectories), were associated with a flow from over the Ocean to the NE. When the trajectory was extended to 48 hours it showed that urban areas to the N and NW might have contributed to the ozone problem in the Norfolk area. From 7 to 8 a.m. on the 19th to 9 to 10 p.m. on the 20th there were only two brief periods when the concentrations dipped slightly below the NAAQS. Because high concentrations persisted through the night, trajectories for 7 p.m. on the 19th and 1 a.m. on the 20th are included and are shown with the trajectories for the 20th. The 4 trajectories, from 7 p.m. on the 19th to 1 p.m. on the 20th, show that the air prior to its arrival in Norfolk was over the Ocean for at least 36 hours. However, it is apparent that all of the air had passed over urban complexes to the N; air from the urban source areas arrived by a circuitous route. The air arriving on the 21st had much more than a 48-hour history over water, and there are no indications of its prior movements; the end point of each trajectory is more than 300 km from land.

Other meteorological phenomena combined with long range transport to play an important role in this episode, particularly during the nocturnal period of August 19-20 when concentrations remained high. There were low clouds, bases at or below 300 meters, and winds averaging 4 mps when these high nighttime readings occurred. It is assumed that with these clouds and winds, the surface-based layer of air did not become stable and that vertical mixing occurred as it did during the daytime. On the 20th, the winds were strong, averaging 7 mps from the Ocean. These strong winds indicate that local emissions would have played a minor role in the high concentrations as the locally generated precursors would have been moved out of the Norfolk

area before the ozone would have formed[6].

The high concentrations during this episode, in spite of the circuitous routes shown by the trajectories, were associated with prior air movement over urban source areas to the N and NW. It is interesting that in a number of cases there was no contact with a potential source of ozone or its precursors for as long as 36 hours before reaching Norfolk, yet the high concentrations were still observed when this air from over the urban complexes reached the monitoring stations. The findings for August 20 were particularly interesting because strong winds which would have minimized the contribution of local emissions occurred in conjunction with prolonged periods of flow over the Ocean; the contribution of long range transport was a major factor, if not the sole source, of the high concentrations observed in Norfolk on this day.

REFERENCES

1. Bandy, A. R. Briefing for State Air Pollution Control Board Concerning Old Dominion University Monitoring Program. Report of Old Dominion University, Norfolk, Virginia, 1973, 6 pp.

2. State Air Pollution Control Board, Ambient Air Quality Data. Annual Report 1974. Commonwealth of Virginia, Richmond, Virginia, 1975, 98 pp.

3. Heffter, J. L., A. D. Taylor, and G. J. Ferber. A Regional Continental Scale Transport, Diffusion and Deposition Model. NOAA Tech. Memo. ERL-ARL-50 Air Resources Laboratories, Silver Spring, MD 28 pp.

4. Middleton, J. T., J. B. Kendrick, and H. W. Schwalm. Injury to Herbaceous Plants by Smog or Air Pollution. Plant Disease Reporter, 34 (9): 245-252, 1950.

5. Chock, D. P., T. R. Terrell, and S. B. Levitt. Time series Analysis of Riverside, California Air Quality Data. Atmos. Environ., 9: 978-989, 1975.

6. Middleton, J. T. and A. J. Haagen-Smit. The Occurrence, Distribution, and Significance of Photochemical Air Pollution in the United States, Canada, and Mexico. J. Air Poll. Control Assoc. 11 (3): 129-134, 1961.

7. Anlauf, K. G., M. A. Lusis, H. A. Wiebe, and R.D.S. Stevens. High Ozone Concentrations in the Vicinity of Toronto, Canada. Atmos. Environ., 9: 1137-1139, 1975.

8. Tiao, G. C., M. S. Phadke, and G.E.P. Box. Some Empirical Models for the Los Angeles Photochemical Smog Data. J. of Air Poll. Control Asso., 26: 485-490, 1976.

9. Lyons, W. A. and H. S. Cole. Photochemical Oxidant Transport: Mesoscale Lake Breeze and Synoptic-Scale Aspects. J. Appl. Meteor., 15: 733-743, 1976.

10. Lea, D. A. Vertical Ozone Distribution in the Lower Troposphere Near An Urban Complex. J. Appl. Meteor., 7: 252-267, 1968.

11. U.S. Department of Commerce, National Weather Service, Norfolk, Virginia. Surface Weather Observations (Forms MF 1-10A and MF 1-10B). Copies of the original records for July and August 1974. 142 pp.

12. U.S. Department of Commerce, National Oceanic and Atmospheric Administration. Local Climatological Data. Published monthly for Norfolk, 1974, 1975. 2 pp.

13. U.S. Department of Commerce, National Oceanic and Atmospheric Administration. Daily Weather Maps. Published weekly, 1974, 1975. 8 pp.

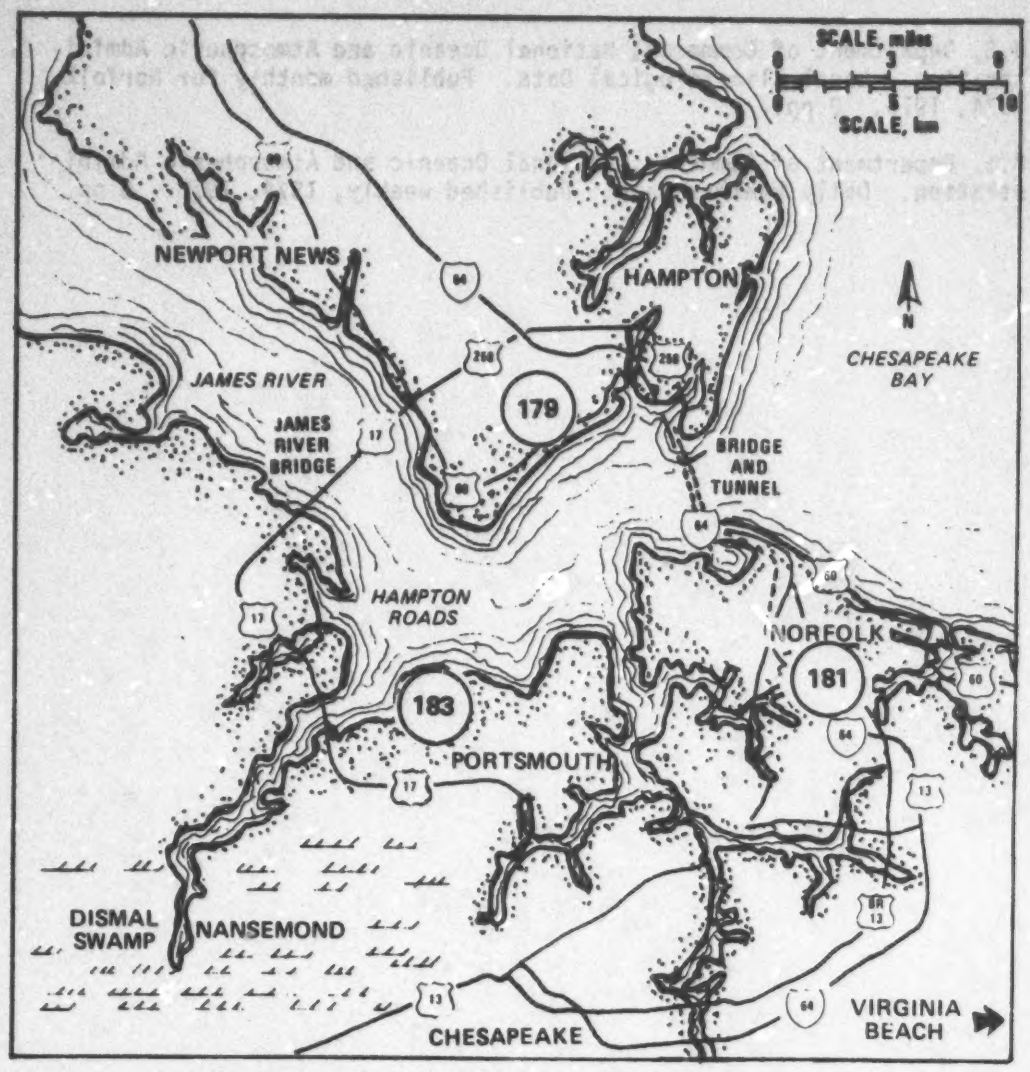

Figure 1. Ozone sampling stations, Norfolk area.

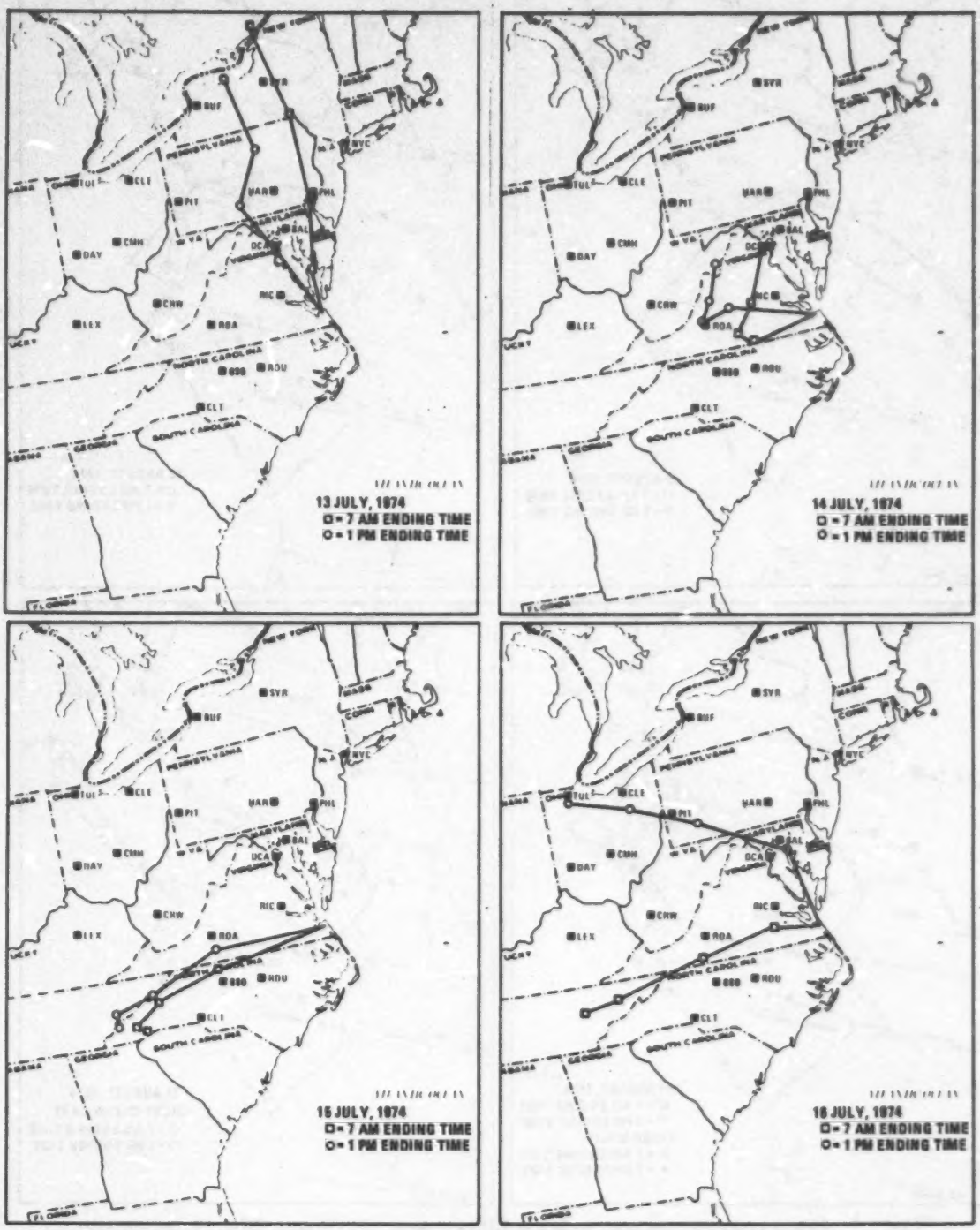
13 JULY, 1974
□ = 7 AM ENDING TIME
○ = 1 PM ENDING TIME
14 JULY, 1974
□ = 7 AM ENDING TIME
○ = 1 PM ENDING TIME
15 JULY, 1974
□ = 7 AM ENDING TIME
○ = 1 PM ENDING TIME
16 JULY, 1974
□ = 7 AM ENDING TIME
○ = 1 PM ENDING TIME

Figure 2. 48-hour backward trajectories, surface to 700 meter layer, 13-16 July, 1974. 12-hour intervals.

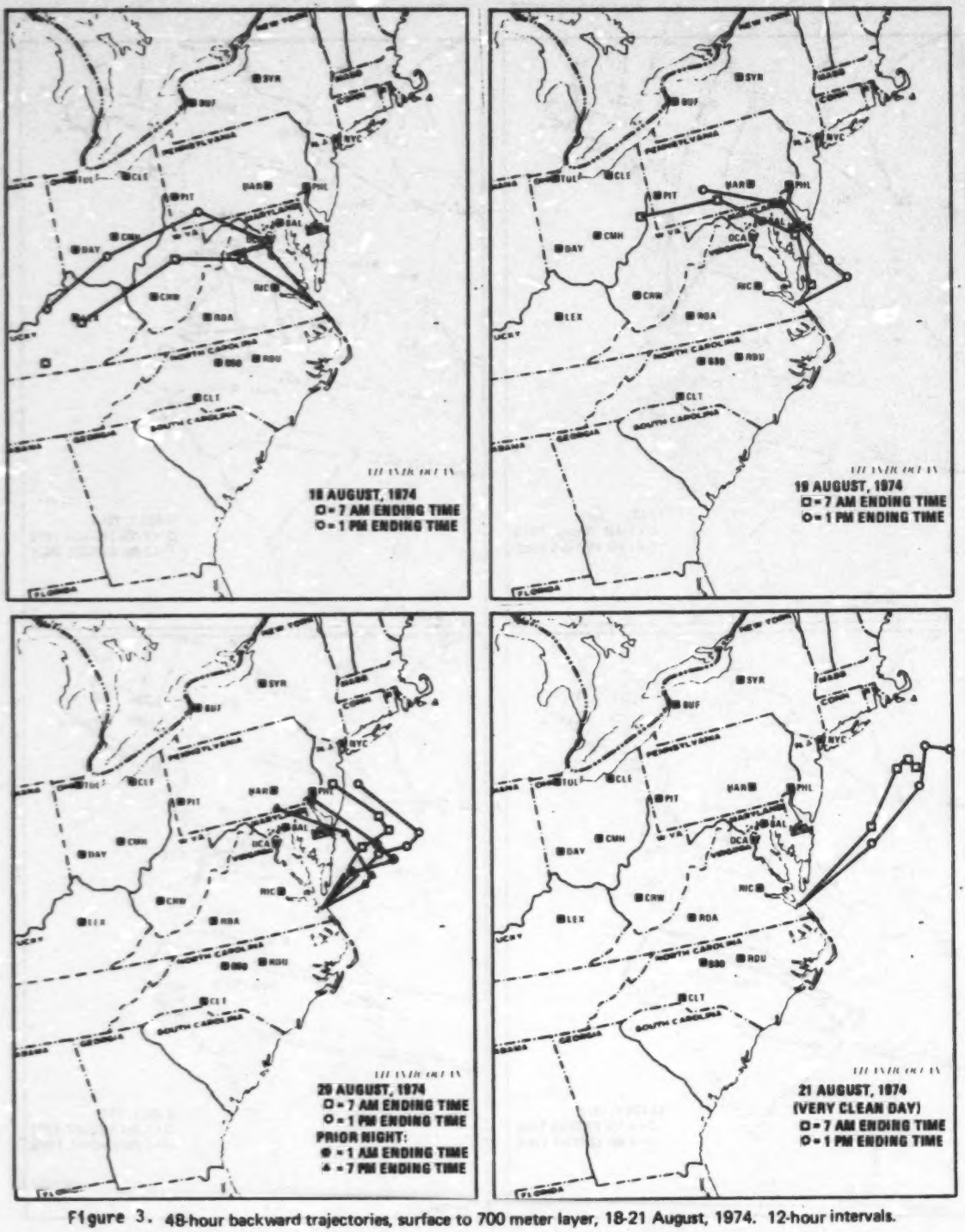
18 AUGUST, 1974
□ = 7 AM ENDING TIME
○ = 1 PM ENDING TIME
19 AUGUST, 1974
□ = 7 AM ENDING TIME
○ = 1 PM ENDING TIME
20 AUGUST, 1974
□ = 7 AM ENDING TIME
○ = 1 PM ENDING TIME
PRIOR NIGHT:
● = 1 AM ENDING TIME
▲ = 7 PM ENDING TIME
21 AUGUST, 1974
(VERY CLEAN DAY)
□ = 7 AM ENDING TIME
○ = 1 PM ENDING TIME

Figure 3. 48-hour backward trajectories, surface to 700 meter layer, 18-21 August, 1974. 12-hour intervals.

TABLE 1. MAXIMUM AFTERNOON OZONE CONCENTRATION AND PAST 24-HOUR AIR MOVEMENT

	July														
Date	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Hampton[1]	80	120	75	30	10	10	50	125	60	55	75	30	80	125	70
Nansemond[1]	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
Norfolk[1]	M	M	M	M	20	20	45	150	75	80	80	70	100	140	100
Trajectory[2]	WSW	WSW	WSW	WSW	SSW	SSW	W	NW	NW	W	N	N	NNW	W	W
Upwind City[3]								RIC	RIC		PHL	PHL	DCA		

	July														
Date	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Hampton[1]	85	85	90	80	85	95	90	60	80	115	60	50	45	50	80	195
Nansemond[1]	M	M	M	40	65	75	80	40	55	70	45	40	30	40	70	150
Norfolk[1]	95	80	70	80	85	90	90	55	120	150	80	10	10	35	95	0
Trajectory[2]	N	N	NNW	SSW	N	NNE	NNE	E	SSW	SW	S	SSW	SW	NNE	WSW	W
Upwind City[3]	BAL	PHL	DCA		PHL											

	August														
Date	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Hampton[1]	105	50	15	10	50	60	40	135	25	55	50	95	120	70	80
Nansemond[1]	110	40	10	10	45	65	45	80	25	40	35	75	55	65	130
Norfolk[1]	120	65	20	15	50	75	M	20	20	40	45	70	110	75	80
Trajectory[2]	WSW	S	S	S	WSW	WNW	SW	WSW	SW	ENE	NE	NE	W	W	WNW
Upwind City[3]						RIC									RIC

(continued)

TABLE 1. MAXIMUM AFTERNOON OZONE CONCENTRATION AND PAST 24-HOUR MOVEMENT

	August															
Date	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Hampton[1]	120	55	80	115	125	35	20	M	M	M	20	70	85	70	45	55
Nansemond[1]	90	50	75	70	95	35	30	20	40	30	25	60	85	60	35	55
Norfolk[1]	80	55	125	90	135	0	10	M	M	M	M	M	90	5	30	45
Trajectory[2]	SE	SW	NNW	NE	NE	NE	E	SW	SW	SW	S	SW	WSW	WSW	WSW	M
Upwind City[3]			DCA													

Notes:

1. Concentrations in parts per billion
2. Direction from which air in surface-to-700 m layer came (N = North, etc)
3. Urban source over which air likely passed in prior 24 hours

Abbreviations:

BAL - Baltimore, MD
DCA - Washington, DC
PHL - Philadelphia, PA
RIC - Richmond, VA
M - Missing

TABLE 2. METEOROLOGY ON DAYS WHEN THE OZONE STANDARD WAS VIOLATED

Date (1974)	Winds 7 a.m. - 5 p.m. Speed (mps)	Winds 7 a.m. - 5 p.m. Source Area*	Temperature departure (°C) from normal	Position of surface high center relative to Norfolk	Percent of possible sunshine	Occurrence of rain or frontal activity**
July 2	2.8	L→S	2	No high over Eastern U.S.	73	No rain. No front.
July 8	3.4	L→S	1	To the Northwest (Ohio)	91	No rain. No front.
July 13	4.3	L	-2	To the Northwest (Ohio)	93	No rain. No front.
July 14	4.4	L	2	To the West (Kentucky)	100	No rain. No front.
July 15	5.9	L	4	No high over Eastern U.S.	97	No rain. Front passed through area.
July 16	5.4	L→S	0	To the Northwest (Michigan)	40	No rain. Front just south of area.
July 17	4.2	S	-1	To the North (Pennsylvania)	98	No rain. No front.
July 18	4.9	L	-1	To the East (Atlantic Ocean)	25	No rain. No front.
July 20	6.6	S	-3	To the Northwest (Canada)	96	No rain. No front.
July 21	3.0	S→L	-4	To the Northwest (Canada)	64	No rain. No front.
July 22	4.4	S	-3	To the North (New York)	97	No rain. No front.
July 24	4.0	L→S	-1	No high over Eastern U.S.	3	Light rain. Front over area late in day.
July 25	4.7	L→S	-1	No high over Eastern U.S.	57	Light rain. Front just south of area.

(continued)

TABLE 2. METEOROLOGY ON DAYS WHEN THE OZONE STANDARD WAS VIOLATED

Date (1974)	Winds 7 a.m. - 5 p.m. Speed (mps)	Winds 7 a.m. - 5 p.m. Source Area*	Temperature departure (°C) from normal	Position of surface high center relative to Norfolk	Percent of possible sunshine	Occurrence of rain or frontal activity**
July 30	4.7	L→S	1	No high over Eastern U.S.	21	Heavy rainfall. Front passed through area.
July 31	2.9	V	0	To the northwest (West Virginia)	34	No rain. Front near area.
Aug 1	3.0	S	1	To the West (Virginia)	22	Light rain. Front near area.
Aug 8	2.5	S	-3	Over Hampton Roads	19	Rain late in day. Front near area.
Aug 12	3.2	S	-5	To the West (Virginia)	91	No rain. No front.
Aug 13	3.0	L→S	-2	To the Southwest (Virginia)	12	Light rain. No front.
Aug 15	3.3	L→S	2	To the North (Canada)	77	No rain. Front in area.
Aug 16	3.4	S	1	To the North (Maine)	60	No rain. No front.
Aug 18	4.0	L→S	0	To the West (Virginia)	61	No rain. Front in area.
Aug 19	3.9	S	-1	To the Northwest (Maryland)	10	Light rain. No front.
Aug 20	6.8	S	1	To the North (Canada)	74	No rain. No front
Aug 28	3.9	L	4	To the West (Virginia)	68	No rain. No front.

* Source Areas
L - Offshore (180°-350°) Flow
S - Onshore (360°-170°) Sea Breeze Flow
L→S - Offshore Followed By Onshore Flow
S→L - Onshore Followed by Offshore Flow
V - Flow Did Not Persist From Any Direction

**In The Norfolk Area